Acoustic metamaterials and future research challenges

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Abstract

In this work, we explore acoustic metamaterials (AMM), a fairly new and active field of research. Initially, we present an overview of the advances in the field and explain the metamaterial properties. Then, we delve further and focus on the sound absorption and insulation applications of these materials. Finally, we report on the current state of knowledge, present the problem of the narrow band efficiency of AMM and give possible solutions based on the literature.

History of acoustic metamaterials and why they are important

Acoustic metamaterials are materials with unusual properties that can manipulate sound in unconventional ways and achieve effects not found in nature. They are important, because they can help address long-standing engineering challenges in acoustics such as minimising the influence of an apparatus on a measurement or eliminating scattering from an acoustic sensor. These are just a few of their applications. Furthermore, some of the reported traits of these materials are: negative refractive index, perfect sound absorption and cloaking. The material properties that give rise to such unusual effects are the effective mass density (ρ) and bulk modulus (κ). Research in the field was originally motivated by parallel developments in electromagnetism [1]. Victor Veselago first proposed the concept of metamaterials and acoustic metamaterials analytically in 1967 [2] and the first acoustic metamaterial (sonic crystals) was fabricated in 2000 [3]. These sonic crystals worked on the principle of negative κ. Later, Li et al. (Li, 2004) proposed a double negative metamaterial (negative ρ and κ) and in 2009 a double negative ultrasonic lens with negative index was constructed, demonstrating the practical application of AMM [5].

What is currently known?

What is it that enables AMM to have such extraordinary properties? This is due to the extra degrees of freedom (DoF) that are hidden in the metamaterials' microstructure. Dynamic subwavelength elements such as Helmholtz resonators, resonant scatterers and elastic membranes are carefully arranged within the material to give them the desired properties. The contributions of each individual microscopic element add up to produce larger effects. Helmholtz resonators are important structures in the field and are used vastly. Their structure and function will be explained later. Resonant scatterers are gratings of metallic spheres or cylinders, which are coated with soft materials. Elastic membranes are thin pliable sheets of material that are contained in a unit cell and have negative effective mass density.

The key to the unusual properties of AMM is that the values of the effective density and bulk modulus can be negative. This means that the particles accelerate in the opposite direction to the applied force and that the medium expands upon compression. But, how is this possible? These parameters can be made negative, when we use unit cells that are smaller than the wavelength of the phonons. At sufficiently low resonant frequencies the negative bulk modulus and density correspond to unit-cell accelerations and deformations that lag in phase compared to the applied force. The phase lag can be attributed to the difference in speed of sound travelling through the inclusions and the medium. These systems are governed by Mie resonances, which are a result of waves scattering from homogeneous spherical particles. The monopolar resonance creates the negative bulk modulus and the dipolar resonance is responsible for the negative density. [6]

So far we have only thought of these systems qualitatively, but how would we model them? It turns out that they can be described by oscillating springs attached to masses. Figure 1 shows the arrangement and the concept of hidden degrees of freedom, which are represented by the smaller mass-spring systems. Figure 1e and 1f illustrate the negative effective properties that arise, when the driving frequency passes the highlighted regions representing resonance. Figure 1e shows an object with negative effective mass in the orange region, whereas Figure 1f shows a spring that has negative effective stiffness in the blue region. [7]

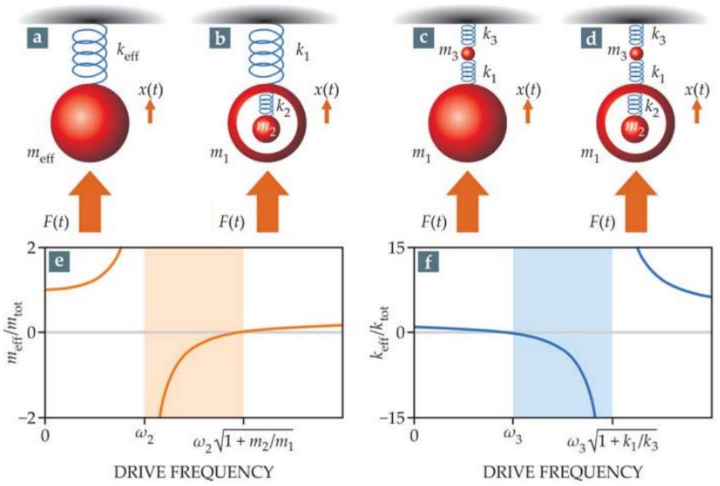

Figure 1: a,b,c,d show mass-spring arrangements. e shows the variation of the effective mass as a fraction of the total mass and f shows the variation of the effective spring constant k as a fraction of the total spring constant as the drive frequency changes.

It turns out that by modelling AMM as mass-spring systems we can derive expressions for the effective density and bulk modulus.

The effective density is given by:

$$\rho_{eff} = \frac{1}{V}\left(m_1 + \frac{k}{\omega_0^2 - \omega^2}\right) \qquad (1),$$

where V is the volume the of the system, m_1 is the mass of the shell as shown in Figure 1, ω_0 is the local resonant frequency, ω is the angular frequency and k is the spring constant. ω_0 is given by $\sqrt{k/m_2}$, where m_2 is the mass representing the hidden degree of freedom in Figure 1. The effective density will be negative in the range $\omega_0^2 < \omega < \sqrt{\frac{k}{m_1} + \omega_0^2}$. This model shows that the negative effective density arises when we consider the two-object system from Figure 1 as a homogenous one-object system.

The reciprocal of the effective bulk modulus is given by:

$$\kappa_{eff}^{-1} = \kappa_0^{-1}\left(1 - \frac{f\omega_0^2}{-\omega_0^2 + \omega^2 + i\Gamma\omega}\right),$$

where κ_0 is the bulk modulus of the material, f is the geometric factor and Γ is the dissipation loss. The effective bulk modulus becomes negative, when the system oscillates near the resonant frequency. [8]

The speed of sound in the metamaterial is given by the square root of the bulk modulus divided by the density. If one of the values is negative then the phase speed is imaginary, which corresponds to exponential decay of the sound wave. These materials do not allow sound to be transmitted and therefore they make excellent absorbers. If both parameters are negative then the phase speed is real, but the energy and phase velocity are in the opposite direction. Such AMMs are capable of negative refraction and therefore they can be used to construct superlenses. These can be utilised in acoustic imaging devices, because they provide subwavelength resolution [1]. Figure 2 shows the applications of acoustic metamaterials depending on the value of their effective density and bulk modulus [7].

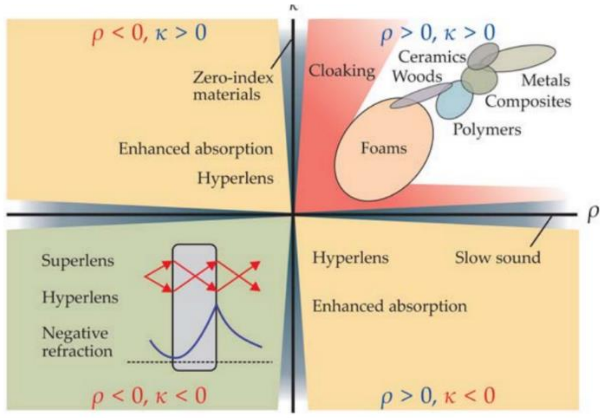

Figure 2: Each quadrant shows the applications of acoustic metamaterials with positive or negative values of effective density and effective bulk modulus.

Superlenses

Double-negative AMM exhibit negative refractive index and can be used to construct superlenses, which can image beyond the diffraction limit. These lenses permit us to amplify the amplitude of the evanescent waves, which decay away from the object, and provide us with subwavelength resolution [8]. We can understand negative refraction by thinking about the group velocity and the phase velocity. The group velocity is parallel to the phase velocity on one side of the interface and anti-parallel one the other, thereby causing the energy flow to switch directions along the interface [1]. Some potential applications of superlenses are sonar sensing, ultrasonic imaging and non-destructive material testing. One major limitation is that the object has to be placed in the near field of the lens in order to amplify the evanescent waves.

The Helmholtz resonator

Figure 3 shows a schematic diagram of a Helmholtz resonator. It is composed of a cylindrical neck and a hollow cavity, which can interact with the outer pressure field via the neck. Its function is to attenuate the sound wave of a particular frequency, which is set by the geometry of the resonator. It is usually be modelled as a mass-spring system, where the air in the neck acts as the mass and the cavity acts as a spring of stiffness k [9]. The air in the cavity is continuously compressed and then rarefied above and below atmospheric pressure. This causes the mass of air in the neck to oscillate.

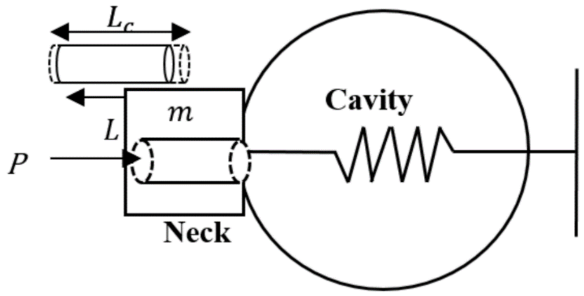

Figure 3: Schematic representation of a Helmholtz resonator. It shows a neck of length L attached to a cavity, which is represented as a spring.

Acoustic metamaterials as absorbers and insulators

In this section, we will briefly consider some of the advances that have been made in the field of AMM sound absorbers and insulators so far. Research in the field is driven by the potential applications that AMM might have in industry and so the interest is focussed on the 50-4000 Hz frequency band. The aim is to study and develop materials that are feasible and affordable rather than materials that require idealised configurations. [10]

In the case of absorbers, what we are looking for is materials that absorb sound waves, attenuate them and minimise the reflection at the low frequency band. One way of doing this is to combine several materials, but this very quickly increases the thickness of the material. Many studies have proposed periodic layered materials that perform well in low frequencies, but are not as efficient in higher frequencies [11]. A different study considered the performance of rigid frame porous media with small inclusions. These combine the strong attenuation of a porous medium and the ability to trap sound waves between the inclusions. The disadvantage of such materials is that they reflect almost all higher frequency waves [12]. This configuration can be modified further by replacing the inclusions with a split-ring resonator (SR). This enhances absorption, because the SR traps energy within it due to resonance. Moreover, it has been shown that if we mix SRs with different resonant frequencies, we can achieve absorption in the 1500-3500 Hz band [13, 14].

In the industry there is a demand for isolation AMM, which in contrast with regular materials, are lighter and have good low frequency performance. Phononic crystals are popular candidates, but they do not cover all the frequency range (50-4000 Hz) [15]. Alternative materials are multi-resonant sonic crystals, which have scatterers embedded in the structure, so they cover larger band gaps. The drawback is that they work as frequency filters, thereby transmitting perfectly all waves with frequencies outside the bandgap [16]. It has been shown that if we instead combine SRs with a porous material we can achieve attenuation in 500-2500 Hz band [17, 18]. Furthermore, there has been research into membrane-type metamaterials, which seem to be efficient at a low frequency range. They are usually composed of a periodic arrangement of membrane resonators. If the resonators have different resonant frequencies then it is possible to cover the 50-4000 Hz band [19].

In this section, we have discussed various absorption and isolation AMM that have the potential to be used in industry and we can conclude that coupling different materials with resonant scatterers can partially solve the problem of narrow frequency bands. However, in the real world we have to design finite samples with imperfect boundary conditions and therefore some of the efficiency is lost. Additionally, we want to use these materials for diffuse sound fields, but we can only simulate periodic fields due to the non-random nature of the simulations. [10]

What is still unknown?

In a 2021 review, titled “Advances in Acoustic Metamaterials”, the authors point out one of the significant challenges remaining in the field of acoustic metamaterials, which is that they are only effective in narrow frequency ranges. They hypothesised that coupling acoustic metamaterial constructs with traditional acoustic architecture can broaden the frequency ranges and they quoted four research papers as supporting evidence [20]. In this section, we take a closer look at the AMM highlighted by the authors as promising candidates in the field of absorbers and insulators. Furthermore, we will emphasise their importance for future research as well as their limitations.

In a 2016 paper [21], researchers reported experimental evidence of broadband perfect absorption, when Helmholtz resonators were combined with a viscoelastic porous plate. Figure 4 shows the setup. The Helmholtz resonators are used to build the side resonant coupling geometry and the porous plates to build the in-line geometry. The perfect absorption was due to the combination of energy dissipation at the resonant modes and the inherent losses of the system. Moreover, the experimenters exploited the mechanism of critical coupling, which predicts that perfect absorption can be achieved when the transmitted and internal fields interfere destructively. The broadband frequency is approximately 500-2000 Hz, so we can conclude that this study is an important experimental step in tackling the problem of narrow frequency ranges in absorbers [21].

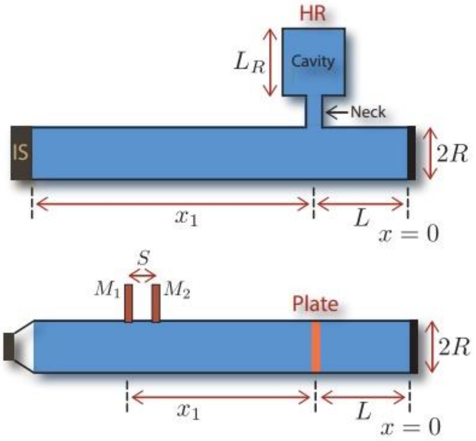

Figure 4: Shows the side and in-line resonant coupling geometries. L is the length of the cavity, L_R is the length of the neck of the HR and R is the radius of the plate.

Another group [22] created a simulation of spider web-structured labyrinthine acoustic metamaterials (Figure 5) in order to study its absorption and reflection characteristics. The structure consists of sectorial circular-shaped labyrinthine channels, a surrounding square frame and internal cavities. It was reported that the addition of the frame provided increased reflectivity and that the structures with a combination of a large cavity and thin curved channels can represent very effective broadband low-frequency sound absorbers. Another advantage of this method is that the wave manipulation performance can be tuned. For example, they can be tuned to only allow manipulation of waves with frequencies 400-600 Hz. These materials can be used as lightweight acoustic barriers with enhanced broadband wave-reflecting abilities for noise reduction. However, one important limitation is that the model does not account for viscoelastic losses. This study demonstrates that the structures described above could be potentially constructed and used as broadband sound absorbers and insulators for airborne noise reduction [22].

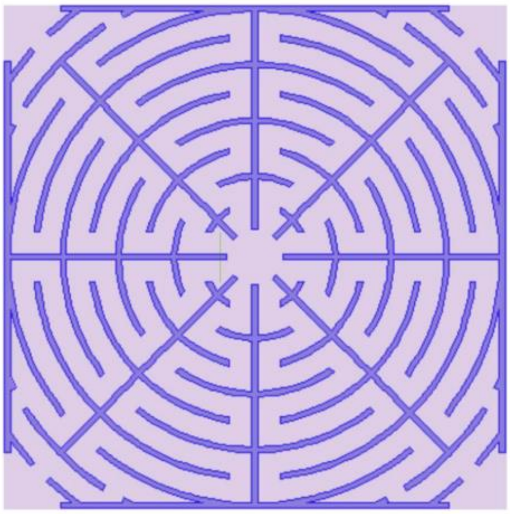

Figure 5: Diagram of spider web-structured labyrinthine acoustic metamaterial.

A 2018 study [23] developed an analytical model to verify previously observed phenomena of lightweight adaptive metamaterials. The results show that the broadband absorption range is 10-2000 Hz. The model consists of a thin plate that has masses attached to it via a hybrid shunted piezoelectric stack, which is modelled as a spring with a negative frequency-dependent stiffness coefficient k (Figure 6). The parameters of the shunting circuit can be finely tuned to enhance sound transmission loss and broadband sound blockage. The authors suggest that the advantage of such metamaterials is that they are lightweight and practically realisable, so they can be used for broadband noise isolation. However, they emphasise that achieving broadband sound isolation with lightweight structures still remains a challenge that has not been entirely resolved [23].

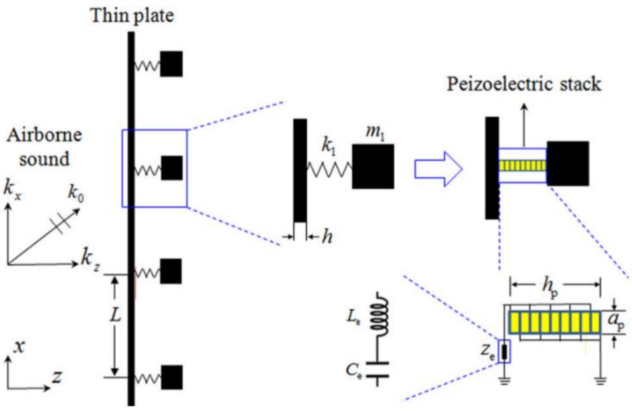

Figure 6: Schematic diagram of the AMM model, which consists of a thin plate with mass-spring resonators attached to it. The piezoelectric stack is modelled as a spring with stiffness k.

Most recently, a new type of lightweight acoustic metamaterial has been proposed by a different group [24]. This is a low-frequency membrane-type acoustic metamaterial with multi-state anti-resonance modes, which is very effective at broadband sound insulation. It has been shown than it can insulate broadband noise between 48 and 736 Hz. The group first simulated the metamaterial and then constructed a large-scale membrane-type plate sample to experimentally verify its broadband frequency transmission loss properties. The simulation and experimental results are in close agreement, but there are deviations in both the signal transmission loss amplitudes and frequencies. This is because damping is difficult to be quantified and simulated. This work shows that it is possible to produce such materials and, as mentioned by the authors, it may promote further research into engineering applications [24].

These four studies [21-24] show that there has been promising research in order to broaden the efficiency frequency range of AMM for applications concerning sound absorbers and insulators. The first [21] and forth [24] studies show experimental advances and the second [22] and third [23] studies model AMM that could potentially be constructed. It is clear that further research is needed in order to build materials that are feasible and have practical applications in industry.

Conclusions

This article has been a presentation of the field of AMM and an analysis of the current state of knowledge. We explored what gives these materials their unusual properties and have associated these systems with mass-spring models, so that we could construct a framework to quantitively describe them. Then, we identified one of the major challenges in the field, which is the narrow frequency band efficiency of absorber and insulator AMM. Researchers have focussed on coupling AMM constructs with traditional acoustic architecture to solve this problem. It is evident that significant advances have been made so far, but further research is needed in order to build AMM that can be used in the industry.

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